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LONG - TERM VICARIOUS CALIBRATION EFFORTS OF MERIS AT RAILROAD VALLEY PLAYA (NV) - AN UPDATE

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ABSTRACT

The launch of ESA's ENVISAT in March 2002 was followed by a commissioning phase for all ENVISAT instruments to verify the performance of the instruments and recommend possible adjustments of the calibration or the product algorithms before the data was widely distributed. Long-term activities to assess MERIS' performance are ongoing. Several vicarious calibration (VC) experiments for MERIS were performed by the Optical Sciences Center, University of Arizona, and the Remote Sensing Laboratories, University of Zürich during summer 2002 and 2003 0. The purpose of such activities is the acquisition of in-situ measurements of surface and atmospheric conditions over a bright, uniform land target, preferably during the time of MERIS data acquisition. The experiments were performed on a well monitored reference calibration site (Railroad Valley Playa, Nevada, USA), which has previously been used to calibrate most relevant satellite instruments (e.g., MODIS, ETM+, ASTER, Hyperion). In-situ data were used to compute top-of-atmosphere (TOA) radiances which were compared to the MERIS TOA radiances (Level 1b full resolution product) to determine the in-flight radiometric response of the on-orbit sensor. In order to assess long-term radiometric performance of MERIS data, nine MERIS scenes acquired over Railroad Valley Playa during July to November 2004 were investigated. In addition, *spatial and temporal uniformity* and *radiometric temporal stability* of the Playa test site, being important for long-term control of satellite sensor data, were investigated using numerous MERIS scenes dating between 2002 and 2004.

1. INTRODUCTION

The Medium Resolution Imaging Spectrometer (MERIS) 0 is one of totally ten instruments on board ESA's ENVISAT platform 00. MERIS is a 68.5° field-of-view pushbroom imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300 m in full resolution (FR) and 1200 m at reduced resolution (RR) in totally 16 spectral bands covering the visible and near infra-red region of the electromagnetic spectrum. MERIS allows global coverage of the Earth in 3 days. MERIS data products provided by ESA include georeferenced TOA radiance data (Level 1b), various water 0, land 00 and atmospheric products 00 (Level 2), as well as analytical tools for end users to access the data 00. The radiometric data quality of MERIS 0 is based on several calibration efforts, including on-board diffuser calibration 00 and vicarious calibration 000, amongst others. Long-term assessment of MERIS sensor performance is important for the quality of derived land products 0.

2. EXPERIMENT DATA AND METHODS

2.1. Study Site: Railroad Valley Playa

The dry lakebed of Railroad Valley Playa (RRVP), Nevada, USA is located at 1.35 km above sea level (38.504° N latitude, 115.692° W longitude). It is a desert site with no vegetation. Temporal records for this site show reflectance variations as a function of time of year, with lowest reflectance in the winter months due to a rising water table. The accuracy of vicarious calibration experiments over land is highly dependent on the choice of an appropriate calibration target. Ideally, such a calibration site should be flat, bright, spatially uniform, and spectrally stable over time, near lambertian for small angles off nadir, and of sufficiently large spatial extent. Desert playas are preferred for vicarious calibration of moderate spatial resolution sensors due to their optical properties, predictably sunny conditions and low atmospheric aerosol loading. In this experiment, in-situ sunphotometer data from all dates of MERIS acquisitions were available.

2.2. Vicarious Calibration

Vicarious calibration is an independent pathway for monitoring instrument radiometric performance, including error assessment with reflectance standards, field instruments and atmospheric radiation measurements. Ideally, vicarious calibration is considered to include all relevant calibration steps that are required to convert raw sensor data into accurate and useful radiometric quantities that are simultaneously measured on ground and at sensor. In general, the experiment follows a reflectance-based approach with ground measurements of the atmospheric optical depth and surface reflectance over a bright natural target 0. For the various 2004 MERIS data sets investigated this study, a best fitting atmosphere from a LUT (characterized by aerosol model and horizontal visibility) is applied for vicarious calibration. MODTRAN-4 00, a radiative transfer code (RTC) is used, constrained by field data, to calculate the top-of-atmosphere radiance at the sensor. Input parameters include ground measurements of the surface reflectance, sun-target-sensor geometries and atmospheric properties (aerosol model, horizontal visibility).

Spatio-temporal radiometric uniformity, as well as *inter- and intra-annual radiometric (temporal) stability* of a test site are fundamental for vicarious calibration, sensor inter-calibration and the long-term radiometric control of satellite sensor data. Optical properties, uniformity and stability of a test site can be affected by different factors such as site surface moisture variations, the capture of water in the upper surface layers, the presence of lichens and vegetation causing spectral changes, variations in the topography generating shade effects or the non-lambertian character of a surface, which increases bidirectional reflectance effects 000.

Given the unavailabilty of spectral ground truth data acquired during any of the 2004 MERIS data acquisitions, ground truth from previous campaigns (summer 2002 and 2003) had to be used in the modelling. As a consequence, the assumption of radiometric uniformity and stability of the test site for equal dates from different years was made. Scott et al. reveiled from a number of images acquired over RRVP at different dates and over many years, that the *spatio-temporal radiometric uniformity* of the site is maintained from mid-summer to the end of the year, particularly from June to August. However, it has to be noted that important radiometric site variations (reflectance changes) occur. They affect the playa's *radiometric temporal stability* and can be explained by intra-annual, seasonal changes in the state of the surface, caused by soil humidity or structure from winds or rain (see Fig.1, right) 0. It is assumed in this study that such temporal reflectance changes are comparable among different years.

2.3. Testsite Uniformity and Stability Characterization

Radiometric uniformity of a test site can be characterized from a *spatial* and *temporal* point of view. Radiometric site variations, being the result of reflectance changes from one season to another affect *spectral stability* over time. The coefficient of variation (CV) is used to evalute the radiometric spatial uniformity of the test site. The CV is defined by the ratio of the standard deviation (δ) over the average (μ). The CV permits the determination of the spatially and radiometrically most homogeneous area within a certain region of interest by moving a window of a predefined size across an image. However, since the location of the ground measurements for the vicarious calibration experiments is well known and limited to a small area, the search for a specific uniform area within the playa was not necessary. The *spatial radiometric uniformity* is calculated within a 3x3 window (approx. 900 m by 900 m) around the ground truth location for 15 MERIS data sets acquired during August 2002 and November 2004. The *temporal radiometric uniformity* is assessed by comparing the CV's of the various dates over time. A site is considered to be uniform when the CV is 3 % or less 0.

Radiometric (spectral) temporal stability can only be assessed properly in case spectral data from different dates within a year and from various years are available. However, as can be seen in Fig.1 (right), spectral ground truth data is only available for August, September and November 2002, as well as for July 2003. It is obvious, that intra-annual variations of surface reflectance of up to 40% occur. In this study, inter-annual temporal stability is assumed in order to use ground truth data of a specific year for calibration purposes on data sets of different years. Nevertheless, both intra- and inter-annual stability (which can be disturbed by e.g., occasional rainfall during summer months) should be investigated in more detail, given the availability of additional spectral ground truth.

2.4. MERIS Data and Available Ground Truth

Nine full resolution data sets of MERIS, acquired over Railroad Valley Playa between July and November 2004, were used for long-term assessment of MERIS's performance. The data sets are summarized in Tab.1.

Table 1: MERIS Full Resolution data sets (Level 1B) used for long-term radiometric performance evaluation at RRVP in 2004.

Acquisition Date	Acquisition Time (UTC)	Orbit Absolute (Relative)	MERIS Camera Nr.	Sun Zenith [°]	Sun Azimut [°]	Sensor Zenith [°] (off nadir)
July 22, 2004	18:00	12520 (442)	4	29.53	120.58	-17.80
July 28, 2004	18:14	12606 (027)	2	28.49	126.53	7.42
July 31, 2004	18:20	12649 (070)	2	28.09	129.79	15.93
August 6, 2004	18:30	12735 (156)	1	27.79	136.09	33.7
August 25, 2004	18:35	13007 (029)	1	31.82	145.77	37.10
September 4, 2004	18:21	13150 (070)	2	36.23	144.53	17.19
September 20,	18:19	13379 (299)	2	41.42	150.21	12.10
September 23,	18:20	13422 (342)	2	42.37	151.48	21.10
November 1, 2004	17:56	13980 (399)	4	57.28	153.68	-21.50

Since no spectral ground truth data was available for the 2004 VC of MERIS, ground truth from the 2002 and 2003 campaigns had to be used. Tab.2 lists the investigated MERIS data sets and the corresponding spectral ground truth used for the performance assessment of the sensor. The spectral data was acquired on the test site using an Analytical Spectral Devices, Inc. (ASD) Portable Spectrometer to measure the surface spectral hemispherical directional reflectance factor (HDRF) (only in nadir view direction) as a function of wavelength in the spectral range between 350 nm and 2500 nm. The variability in the spectral measurements, due to target inhomogeneity and instrument calibration uncertainties is around ±3% over the 350-1200 nm range (±1 stdev from the mean).

A MERIS full resolution subset of RRVP, acquired on July 31, 2004 is given in Fig.1 (left). The variability of the playa in surface brightness is clearly visible. A homogeneous area (see rectangle) is chosen for spectroradiometric ground truth measurements and the investigation of MERIS TOA radiances in the vicarious calibration process. Fig.1 (right) shows spectral ground truth data of the test site acquired on several dates during 2002 and 2003. Spectral intra-annual variations (up to 40%) of the playa test site occur, resulting from seasonal changes in the state of the surface, as discussed in Chapter 2.2.

Table 2: MERIS FR acquisition dates and corresponding ground truth used for 2004 performance evaluation.

MERIS FR Acquisition Date at RRVP	Corresponding Spectral Ground Truth Used for VC
July 22, 2004	July 22, 2003
July 28, 2004	July 22, 2003
July 31, 2004	July 22, 2003
August 6, 2004	July 22, 2003
August 25, 2004	July 22, 2003
September 4, 2004	September 21, 2002
September 20, 2004	September 21, 2002
September 23, 2004	September 21, 2002
November 1, 2004	November 2, 2002

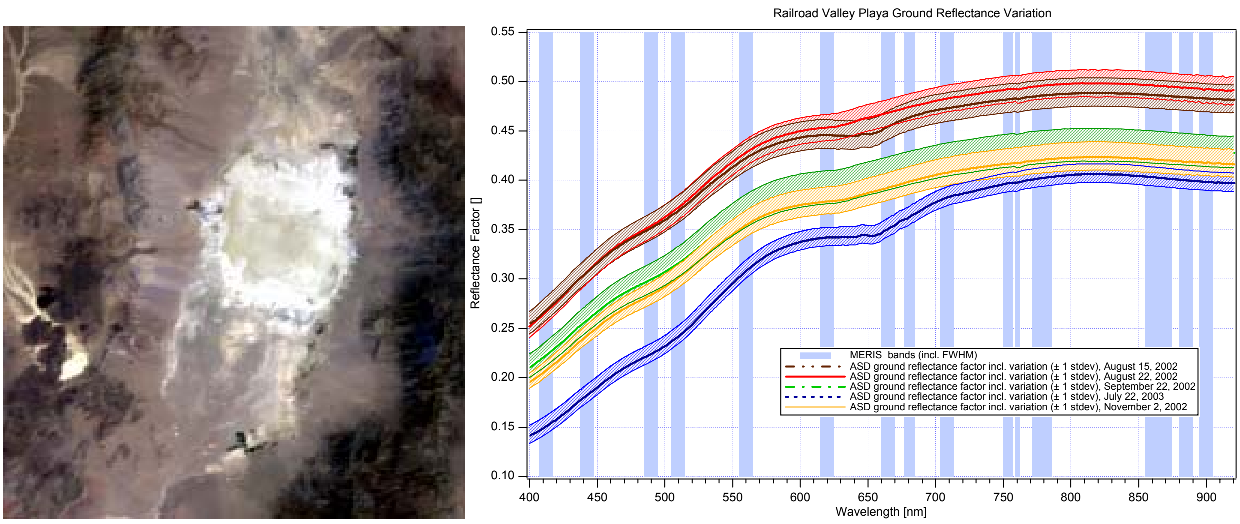

Figure. 1: MERIS Full Resolution subset of RRVP test site acquired on July 31, 2004 (left), Variation of spectral ground truth data from RRVP over time (right).

3. ANALYSIS AND RESULTS

3.1. Radiative Transfer Calculation of TOA Radiance

Due to a limited availability of sun photometer data from the test site, no such data was used for radiative transfer calculation to convert in-situ ground reflectance data to TOA radiances that are compared to MERIS TOA data. Instead, MERIS measured TOA radiances are compared to the results of radiative transfer calculations of the ground truth data to TOA radiance, using a look-up table (LUT) approach. The best fitting atmosphere, characterized by aerosol model and horizontal visibility, is then chosen from minimization of the relative rms error. The reference solar irradiance of Thuillier 0, as adopted for ENVISAT by ESA, is used for the atmospheric modelling. Test site location, data acquisition times and dates, as well as the sun-target-sensor geometries are optimized for the specific ground truth area (9 pixels) in the MERIS data sets.

3.2. Comparison of Ground Truth Measurements to MERIS Observations

Fig.2 shows the results of the MODTRAN modelled top-of-atmosphere radiances from the spectral ground truth data, together with the MERIS measured radiances in the corresponding MERIS bands for a subset of four of the nine MERIS data sets that were investigated in this work. It is obvious that the shapes of the modelled curves and the MERIS measured TOA radiances do not fully match. Especially the first bands (aerosol type sensitive), band 11 (oxygen at 760 nm) and band 15 (water vapour absorption region at 900 nm) are critical in the modelling. These bands need more precise atmospheric reference data (e.g., meteorological data) for improved vicarious calibration. Apart from these bands, the mean relative differences between MERIS measured and radiative-transfer modelled TOA radiances, as they are given in Tab.3, do not exceed 5.48% (except for the July 22, 2004 data).

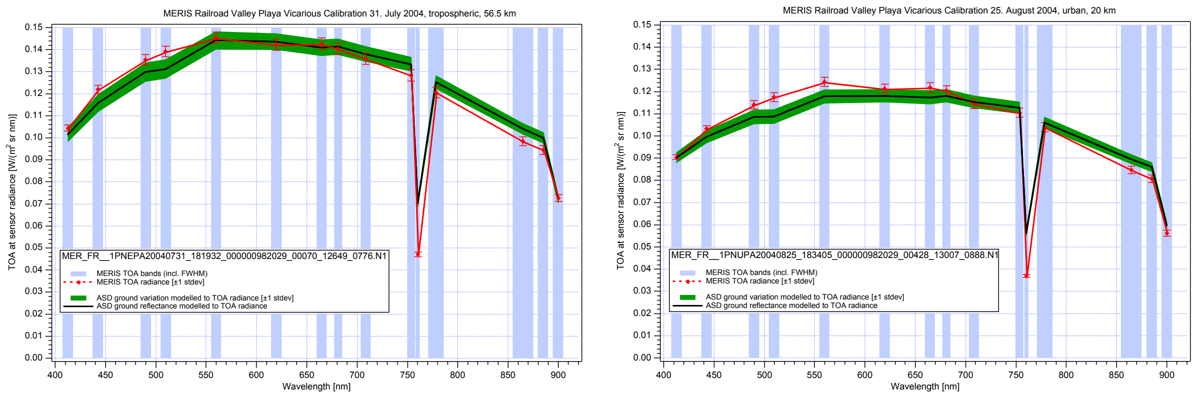

Figure 2: MERIS measured and MODTRAN modelled top of atmosphere (TOA) radiances for July 31, 2004 (top, left), August 25, 2004 (top, right), September 20, 2004 (bottom, left) and November 1, 2004 (bottom, right).

In addition to the relative differences between MERIS measured and MODTRAN modelled TOA radiances, the mean relative rms errors between measured and modelled radiances for all nine dates under investigation are given in Tab.3. By excluding the before-mentioned bands 11 (760.35 nm) and 15 (899.86 nm), the relative rms error can be reduced substantially. The mean relative rms error represents the overall uncertainty of the vicarious calibration method, since all potential error sources account for the quality of the data fit. An error budget is given in Tab.4. While the uncertainty in the knowledge of the solar irradiance, the spectralon reflectance, and the illumination geometry are well known for the testsite 0, uncertainties remain for the relative surface BRF of the specific dates in 2004, as well as the atmospheric characterization during data take. Surface reflectance errors including errors in geolocation, in-situ sampling, test site inhomogeneity and instrument absolute calibration are not included in this error budget, because they are assumed to be represented by the ±3% variability of the spectral measurements (±1 stdev from the mean), as indicated in Chapter 2.4.

Table 3: MERIS and VC TOA radiances differences and rel. rms error for the observed MERIS 2004 data sets.

Differences between MERIS and modelled TOA radiance from VC (%)									
	22. 7. 2004	28. 7. 2004	31. 7. 2004	6. 8. 2004	25. 8. 2004	4. 9. 2004	20. 9. 2004	23. 9. 2004	1. 11. 2004
Mean difference (%)	**11.50**	**6.60**	**6.16**	**7.59**	**7.02**	**8.08**	**6.57**	**6.66**	**9.57**
Excl. channel 11&15	10.30	4.55	3.26	4.75	3.58	5.48	3.04	4.77	5.07
Mean rel. rmse (%)	**11.32**	**8.26**	**9.00**	**9.35**	**9.85**	**8.12**	**8.62**	**7.84**	**11.39**
Excl. channel 11&15	9.06	4.00	3.70	3.96	3.58	5.07	2.35	5.66	5.46

Table 4: Vicarious calibration error budget.

Error Source	Absolute Uncertainty (%)	
	Including all channels	Excluding channels 11 & 15
Solar Irradiance Knowledge	2	
Spectralon Reflectance Knowledge	1.5	
Surface BRF Knowledge and Atmospheric Characterization max. (mean from all dates)	< 11.04 (7.34)	< 8.71 (1.55)
Cosine of Solar Zenith	< 0.1	
Root-mean-square max. (mean from all dates)	< 11.32 (7.75)	< 9.06 (4.31)

3.3. RRVP Uniformity and Stability

Spatio-temporal radiometric variability (uniformity) of the RRVP test site is addressed for a 9x9 pixel window surrounding the calibration area for 16 MERIS scenes between August 2002 and November 2004. Fig.3 shows the bandwise temporal CV for all MERIS channels. Based on the assumption that a site is considered to be uniform when the CV is below 3% (see Chapter 1.3), this rule applies for 13 out the 16 dates. The results are in good agreement with the findings of Bannari et al. 0. Increased mean CV's are found for the two August 22 and August 31, 2002 scenes, as well as the June 4, 2003 scene. It could not be reconstructed from AERONET data whether rainfall had occurred on the preceding days, that may have caused variations in surface reflectance.

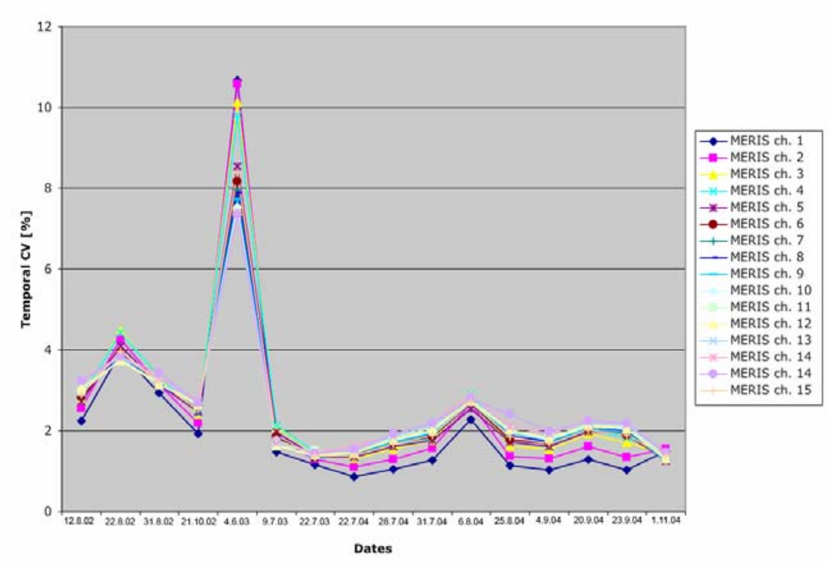

Figure 3: Temporal coefficient of variation (CV) for all MERIS bands calculated from 16 MERIS scenes acquired over RRVP between 2002 and 2004.

A limited inter- and intra-annual assessment of *radiometric (spectral) temporal stability* can be retrieved from Fig.1 (right). Surface reflectance varies up to 40% amongst the available spectral ground truth for the months of July, August, September and October. Some reflectance curves show spectral variations that can be assigned to spectral features, e.g., the chlorophyll absorption feature around 650 nm. Increased absorption in this region could indicate an increased presence of plant material in the test site, such as lichen, shortly after occasional rainfall. These remarkable variations make the use of accurate and timely spectral ground truth an essential requirement for vicarious calibration at RRVP.

4. CONCLUSIONS

Reflectance-based vicarious calibration methods generally have absolute uncertainties of 3-5% 0. It is obvious from this study, that both accurate spectral ground truth and characterization of the atmosphere during a vicarious calibration experiment are crucial to vicarious calibration. The absolute uncertainty of this study's VC activities is below 11.32% (mean of all dates under investigation: 7.75%), based on all MERIS channels. Under exclusion of channels 11 and 15, the method's uncertainty can be reduced to under a maximum of 9.06% (mean of all dates under investigation: 4.31%).

The mean differences between MERIS- and VC- mean TOA radiances do not exceed 10% for any of the dates under investigation, except for July 22, 2004. Exclusion of band 11 and band 15 results in mean differences lower than 5.5% for all data sets (except for July 22, 2004). Apart from band 1 (sensitive to aerosol type, 412.55 nm), band 11 (oxygen band at 760 nm), and band 15 (water vapour absorption region at 900 nm), all bandwise VC results lie within less than 10% of MERIS measured TOA radiances (except for July 22, 2004); most of the bands even lie within a 6% range. The beforementioned MERIS bands need very precise atmospheric characterization for VC. An incorrect assumption about aerosol absorption can strongly affect the VC accuracies of the shorter wavelengths bands.

Stable atmospheric conditions over a certain regional extent and radiative transfer model inversion including non-standard aerosol models (e.g., the influence of black carbon particles) could further improve VC results.

From the results of this multitemporal VC experiment, no need to update the MERIS calibration may be formulated. Although differences between measured and modelled TOA radiances greater than 6% occur in several bands, the uncertainties of the VC method and the accuracy requirements of MERIS absolute radiometric calibration (< 6%) do not allow to suggest a calibration update. Especially due to the fact that no simultaneously acquired spectral ground truth data for the 2004 MERIS data takes were available for VC, the mean uncertainties for the 2004 data were slightly higher than in previous years. This shows clearly the need for accurate and up-to-date spectral ground truth and atmospheric data.

Nevertheless, multitemporal VC bears the potential to monitor the radiometric performance of a sensor over time. Surface HDRF measurements using a goniometer could improve the VC of large field-of-view sensors, since an off-nadir geometry could be modelled more precisely when using directional reflectance data other than from nadir. Spectrodirectional ground truth data should be acquired as close to the time of the sensor overflight as possible, in order to minimize vicarious calibration errors due to spatio-temporal and inter-/intra-annual radiometric variations. Such variations were found to be existent at the RRVP test site.

This study clearly shows the need for a VC experiment to be performed in a very large and homogeneous area (both spectrally and spatially, e.g., desert area) with stable atmospheric conditions. A supposed uniform test site should preferably fill the complete field-of-view of the five MERIS cameras, in order to satisfactorily address the individual camera behaviours and directional effects.

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